Behind the Ergometer Display

revised: January 2008

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We like to “row” on the ergometer because it feels so much as real rowing and not unimportant, we get immediately numerical feed back of our performance. But what is the meaning, the basis and the value and of the numbers on the display? This question is not so easily to answer because Concept is rather chary with information. In the course of time some information was found in the ergometer’s manual and on the Concept website.

The section below replaces some earlier considerations.

The Concept website contains the formula (my notation):

(1) $$P = 2.8 v^3$$

that can also be written as:

(2) $$v = \sqrt[3]{\frac{P}{2.8}} = 0.7095 P^{1/3}$$

with:

P = power supplied to the flywheel [W]

v = “boat” velocity [m/s]

The origin of the coefficient 2.8 in (1) is unclear.

A theoretical basis is strictly speaking not necessary. One will understand that boat speed (statistically) was derived from observations on ergometers and boats. Ergometer readings have to be more or less realistic and to motivate the rower they must indicate a slightly better performance than in the boat. And that is in general the case. It is generally accepted that boat resistance and flywheel resistance is proportional to the second power of speed and thus power is proportional to the third power of speed.

But now the ergometer proper. To determine the power delivered to the ergometer two quantities are to be measured: torque on the fly-wheel shaft and its angular velocity. The measurement of the angular velocity of the fly-wheel is no problem. Standard components are available.

When I saw a Concept ergometer for the first time and I noticed that the power was displayed I concluded that the torque was measured. In a

laboratory this measurement is not a big problem but in the ergometer it is expensive and it makes the machine more vulnerable for failure.
Therefore the torque was and is not measured directly.
The power can be calculated with (3) and it will probably be done in this way in the ergometer's computer:

(3) $$P = C_1 * \omega^3 + \omega * J * \frac{d\omega}{dt}$$

P = the power supplied by the "rower" and transmitted by the shaft [W]
C_1 = a constant [W.s^3]
ω = angular velocity of the fly-wheel [rad/s]
J = moment of inertia of the fly-wheel [kg.m^2]
$\frac{d\omega}{dt}$ = angular acceleration of the fly-wheel [rad/s^2]

The first part of (3) is the power dissipated by the resistance, the second part is the power to accelerate the fly-wheel
At constant speed is $d\omega / dt = 0$ and is $P = C_1 * \omega^3$.
The determination of J is rather simple and the manufacturer has to do it once for a prototype; J does not change in time apart from some dust or dirt deposited on the wheel but this is considered negligible.
C_1 is dependant on the position of the air inlet slide and is subject to change in time due to the deposit of dust and dirt and insufficient lubrication. As far as I know these effects were neglected in the older type Concept ergometers (and still in ergometers of other manufacturers) and the power was calculated with a constant value C_1.

For the newer type of ergometers Concept has solved this problem quite ingeniously. During the recover the fly-wheel decelerates as a result of outflow of energy. From the measured deceleration the value of C_1 can be determined and can then be used, as a good approximation, for the next pull. The influence of the position of the air inlet slide has been covered then correctly. This facility is called PM2 by Concept. Values related with PM2 can be read from the lower right window in the display. PM2 has to do also with the possibility to measure the heart frequency; the connection is unclear to me.

The website of Concept states (for PM2):
'The drag factor can be displayed while you row by holding down the "ready" button and pressing the "rest" button before you begin rowing.'

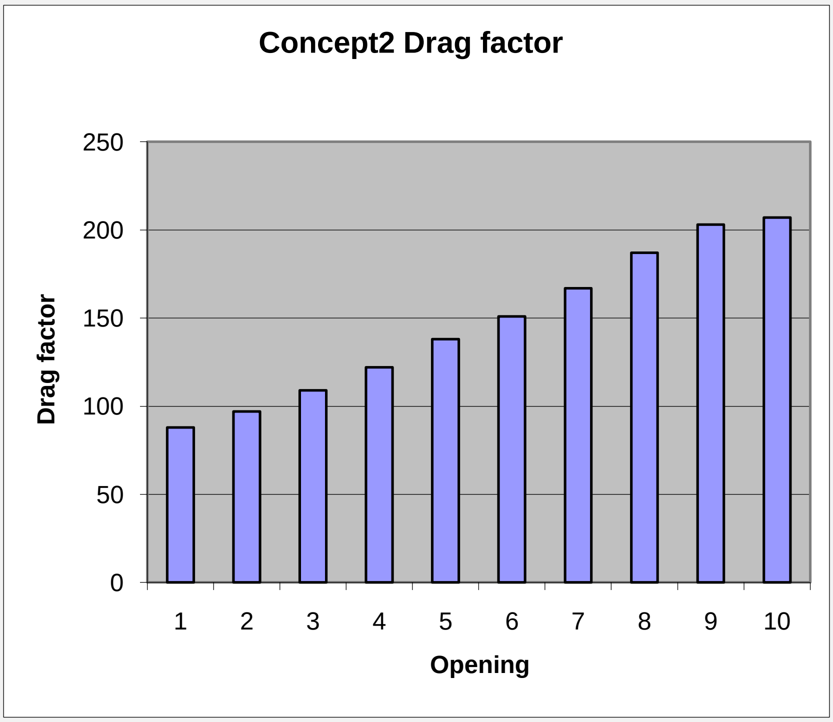
This is not a very clear instruction but by pressing the indicated buttons one will succeed to display the drag factor, related to C_1 in my notation.

For position 1 of the inlet slide I found a value 90, for position 3: 110, for position 10: 196. No units are displayed but this drag factor is not dimensionless and is not identical with C_1 because ω is certainly bigger than 10 rad/s and then yields
$P = C_1 * \omega^3$ a much to big value for the power.

The newer Concepts have the PM3 or PM4 monitors with menu structure. To show the drag factor from the main menu select More Options and then select Show drag factor. The drag factor then appears in a special window without any other quantity. As far as I know this is the only possibility to show this factor in another window during rowing.

I found the following relations between inlet slide position (isp) and drag factor (df):

isp	1	2	3	4	5	6	7	8	9	10
df	88	97	109	122	138	151	167	187	203	207



The bar chart shows a slight nonlinearity between these quantities but this can be the result of inaccuracies in the setting of the inlet slide.

From a short e-mail message I received from Concept I might conclude that:

(4) $$P = C_2 * v_k^3 \quad \text{met}$$

C_2 = the displayed drag factor [$W.s^3/m^3$]
v_k = the velocity of the chain during the pull [m/s]

This yields an acceptable value for the power. It is a bit peculiar that Concept offers the possibility to read out the drag factor without providing us with the definition and the unit.

Another complication is that the equations (3) and (4) refer to instantaneous values. During the pull the power is not constant and during the recover the power is nil. The power shown on the display (the central window) is almost certainly the mean power delivered during one complete cycle of pull and recover. At the end of the pull (handle at the stomach) the value of the power is refreshed. Compare this situation with a four-stroke piston engine. Only one out of four strokes produces work; this amount of work is divided by the total cycle time and that is 'the'power.

It is possible that Concept has programmed the following calculation in the processor:

(5) $$P = \frac{\int_{t_1}^{t_2} C_1 * \omega^3 * dt + 0.5 * J * (\omega_3^2 - \omega_1^2)}{t_3 - t_1}$$

t_1 = starting time of the cycle, catch [s]
t_2 = end of the drive, finish [s]
t_3 = end of the cycle, next catch [s]
ω_1 = angular velocity of the fly-wheel at the start of the cycle [rad/s]
ω_3 = angular velocity of the fly-wheel at the end of the cycle [rad/s]

while C_1 has been determined in the previous recover from (5), puting P = 0:

(6) $$C_1 = -\frac{J * \frac{d\omega}{dt}}{\omega^2} \qquad \left(\frac{d\omega}{dt} < 0, \text{ so } C_1 > 0\right)$$

(For a discussion and correction: see Attachment)

Proof: Check after an ergometer session if the presented equations give the same results as the display readings. I found perfect agreement for (1). In the lower left window the mean power [W] during the session is displayed. Multiplied by the duration of the session this yields the total amount of work [J] during the session. This quantity is not displayed. By pressing the button of the units a number with the unit ‘cal’ appears. Meant is ‘kcal’. This is not a straight conversion of units. The Concept website shows the formula (my notation):

$$P_i[\text{kcal/h}] = 4 * 0.8604 * P_o[\text{W}] + 300$$

where:

P_i = internal combustion power in the body of the rower
P_o = power to the flywheel
0.8604 = conversion factor of W to kcal/hr
4 = assume that internal combustion requires four times the externally deliverd power
(efficiency 25%)
300 = assume that a human body in rest (zero external power) consumes 300kcal/h

Some relations between the units are:
1 kcal = 4.1868 kJ
1 kcal/h = 1.1623 W
1 W = 0.8604 kcal/h

The website of Concept is: http://www.concept2.com/us/default.asp

Dr Anu Dudhia, Oxford University, also presents a discussion on ergometer mechanics.

Conclusion: The ergometer is a continuous source of pleasure.

Note: The idea that the energy delivered by the rower is dissipated by drag and friction is in fact not correct, or at least not completely correct. The main outflow of energy is the kinetic energy of an air stream. The ergometer is a kind of ventilator (and not a throttle) that delivers more air and requires more energy when the inlet slide is opened further. Without any kind of friction it would work as well. However, this observation does not invalidate the assumption that power is proportional to the third power of angular velocity and the equations remain the same.

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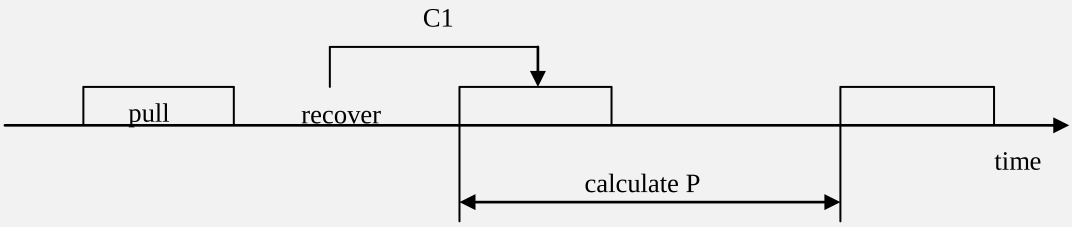
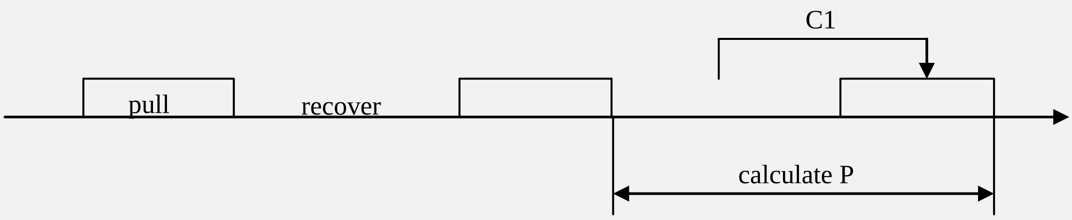
Attachment June 2005

Sébastien Boyas observed that according the above presentation power seemed to be calculated between two consecutive catches. He suggested that considering the fact that the display is refreshed immediately after the finish it is more reasonable that power is calculated between two finishes. The figure below illustrates the difference.



Power calculated between two consecutive catches. Use C1 from the recover in the previous cycle.



Power calculated between two consecutive finishes. Use C1 from the recover in the same cycle.

I think the second possibility is, after considering this figure, the most obvious one.

The results of both methods will not differ very much. Another question raised was: How can a value for the power be displayed after the first pull, when no recover has preceded and so no value for C1 can be available? The possible answer is that for the first pull a default value may be used and it can very well be zero because for the first stroke the increase in kinetic energy is dominant.

Of course the correct answers can be given by Concept.

For the sake of completeness follows a revision of formula (5)

(5) $$P = \frac{\int_{t_2}^{t_3} C_1 * \omega^3 * dt + 0.5 * J * (\omega_3^2 - \omega_1^2)}{t_3 - t_1}$$

t_1 = starting time of the cycle, start of recover [s]
t_2 = end of the recover, catch [s]
t_3 = end of the cycle, finish [s]
ω_1 = angular velocity of the fly-wheel at the start of the cycle [rad/s]
ω_3 = angular velocity of the fly-wheel at the end of the cycle [rad/s]

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